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Account for the contribution of higher modes under system seismic resistance estimation by nonlinear static method

M A Zubritskiy[1], O Y Ushakov[2],L S Sabitov[3,4]

[1] LLC «UralConceptProject», 22 Roza Luxemburg street, Ekaterinburg, 620075, Russia
[2]Ural State University, 19 Mira street, Ekaterinburg, 620002, Russia
[3] Kazan State Power Engineering University, 51 Krasnoselskaya street, Kazan, 420066, Russian Federation
[4]Kazan Federal University, 18 Kremlyovskaya street, Kazan, 420008, Russian Federation

zubrickiy_maksim@mail.ru

Abstract. The article presents higher modes accounting method under estimation of system seismic resistance by nonlinear static method. As part of the study, in order to verify the proposed method for finding the inertial forces modified system a complex of dynamic and static calculations was performed.It is established that proposed inertial forces modified system can significantly reduce system seismic resistance lack.

1Introduction

To find the most unfavorable system response by a nonlinear static method, it is necessary to perform at least two calculations with different inertial horizontal forces distribution along the system height:

- The pattern, based on lateral forces corresponding to the system natural vibrations main form. Seismic evaluation of the system with a given force distribution can be estimated only if the modal mass of the considered form is at least 75%;
- The pattern, based on inertial forces superposition of several vibration forms.In this case, the total modal mass of the considered vibration forms should not be less than 90%;
- The “uniform” pattern, based on lateral forces that are proportional to mass regardless of elevation (uniform response acceleration);
- The “modal” pattern, proportional to lateral forces consistent with the lateral force distribution determined in elastic analysis.

Further characteristic point search on the capacity curve is a laborious process required cumbersome graphs plotting and non-trivial calculations. In modern software package, a non-linear static method is implemented only based on only one inertial forces vibration mode. In addition, the system seismic response for a given impact is significantly less than the dynamic method results.

2 Higher vibrations forms accounting method

To determine the response of the system, taking into account the influence of higher vibration modes, we consider the following method with modified system of inertial forces.

The inertial forces modified system is the system based on forces superposition the SRSS-method, in which the top displacement of considered model will correspond to the total displacements obtained by response spectrum analysis.

According to [5] to destroy a material, no matter what the load is applied, it is necessary to expend the same amount of energy. Thus, the linear system deformation energy with ainertial forces modified system is identical to the system deformation energy, taking into account plastic deformations.

The seismic resistance evaluation next stage is to plot the capacity curve “Force at the base V_b - Displacement of the system top Δ” based on nonlinear static calculation for the system with one degree of freedom under the modified inertial forces system .

3 Problem statement and method testing

Three masses 9-meters high column was selected as representative case study to carry out the performance-based seismic methods evaluation.

As a construction material structural steel was chosen. Stress-strain diagram is shown on Fig. 2. To describe the non-linear behavior of the system elements the model of Bilinear Kinematic Hardening has been adopted. The diagrams of steel deformation under tension and compression are the same. The yield surface is described by the Von-Mises criterion and is a cylinder whose axis coincides with the axis of hydrostatic compression in the axes of the main stresses (Fig.3). Damping parameters were calculated based on 1st and 3rd natural vibration frequency. Dynamic model characteristics are shown in Table 1.

The seismic excitation used for nonlinear time history and pushover evaluations is defined by a set of three strong ground motions:

1. Iran, 1978 г. (Erthq. 1);
2. El Centro, USA (California), 1979 г. (Erthq. 2);
3. Duzce, Turkey, 1999 г. (Erthq. 3).

Accelerogram records were taken from [14].

Table 1. Dynamic model characteristics

№	Nomination	Value		
		Erthq. 1	Erthq. 2	Erthq. 3
1	Cross-section,*mm*	*I-beam 300(h)x200(b)x15(b_f)x8(b_w)*		
2	Height*, mm*	*9000*		
3	Youngmodulus, *Pa*	*$2e^{11}$*		
4	Yieldpoint, *MPa*	*270*		
5	Tangential modulus, *MPa*	*$5.361e^3$*		
6	Masses $m_a = m_b = m_c$, *kg*	*3000*	*10000*	*7000*
7	1st natural vibration frequencyf_1, *Hz*	*0.853*	*0.45094*	*0.5637*
8	2nd natural vibration frequencyf_1, *Hz*	*5.397*	*2.8677*	*3.5813*
9	3rd natural vibration frequencyf_1, *Hz*	*13.799*	*7.3161*	*9.1411*

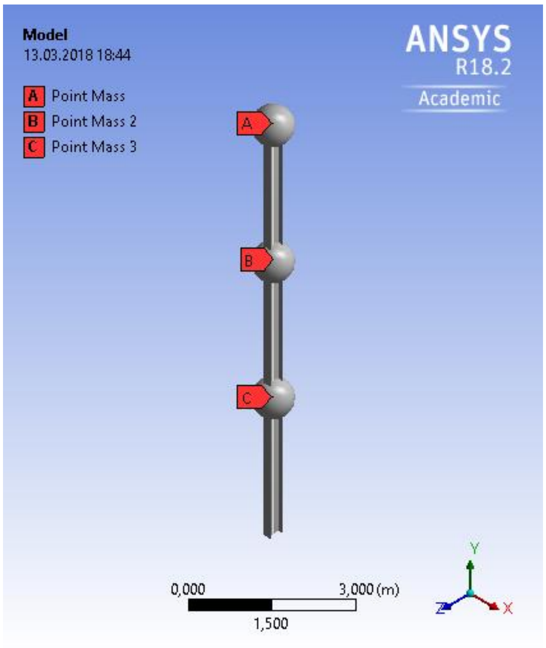

Figure 1. Dynamic model general view

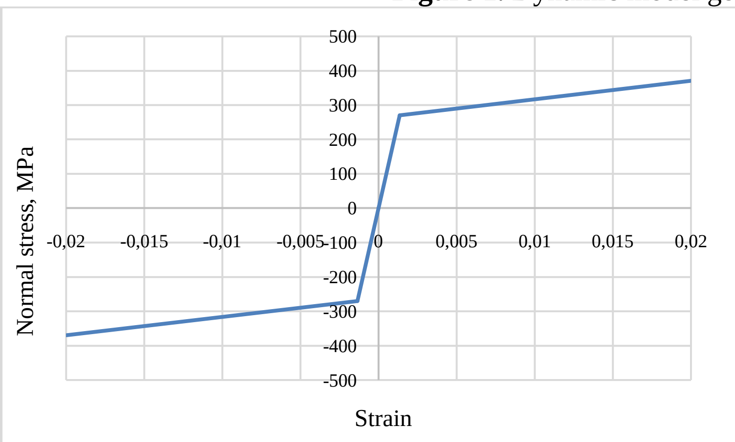

Figure 2. Stress-strain diagram of steel

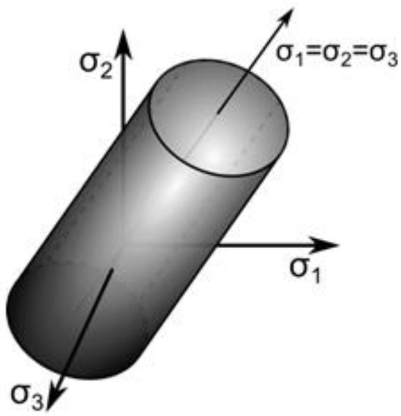

Figure 3. Von-Mises yield surface in the axes of the main stresses

To calculate the forces system for a given system during the seismic evaluation by the multimodal nonlinear static method, the initial data are the inertial forces of the first three vibration modes.

The inertial forces distribution and the forces resulting system for seismic impact Iran, 1978 (Erthq1) are obtained byresponse spectrum analysis.

To calculate the inertial force reduction coefficient, a linear static analysis was performed. The resulting coefficient value and the system's energy consumption is presented in Table 2.

The next step in seismic evaluation is to perform a non-linear static calculation under the action of a inertial forces modified system. Then the capacity curve is plotted in the coordinates of the "shearing force at the base — the top displacement of the system".

The characteristic point search is iterative: it is necessary to find such a point on the capacity curve so that the figure formed under the graph area corresponds to the target system energy consumption.

The results obtained for seismic impacts Erthq1..3 are summarized in Table 2.

Table 2. The results obtained by the multimodal nonlinear static method

№	Nomination	Value		
		Erthq.1	Erthq.2	Erthq.3
1	Inertial force at the upper node, *kg*	*4585.5*	*3492.1*	*3755.7*
2	Inertial force at the middle node, *kg*	*5995.0*	*4310.1*	*4529.5*
3	Inertial force at the lower node, *kg*	*5281.7*	*4112.7*	*3913.2*
4	Upper node maximum horizontal displacement obtained by response spectrum analysis, *mm*	*271.11*	*264.35*	*267.79*
5	Upper node maximum horizontal displacement obtained by static analysis with inertial forces modified system, *mm*	*717.78*	*536.55*	*565.96*
6	Reduction factorα	*0.3777*	*0.49268*	*0.47316*
7	Maximum system termination lateral force under the inertial forces reduced system action, *kN*	*58.754*	*57.57*	*56.602*
8	Potential strain energy / Energy consumption, *J*	*796.41*	*760.93*	*757.87*
9	Upper node maximum horizontal displacement obtained by multimodal pushover analysis, *mm*	*282.0*	*270.85*	*274.0*
10	Middle node maximum horizontal displacement obtained by multimodal pushover analysis, *mm*	*159.66*	*153.08*	*154.2*
11	Lower node maximum horizontal displacement obtained by multimodal pushover analysis, *mm*	*54.69*	*51.75*	*51.95*
12	Maximum bending moment near the anchorage obtained by multimodal pushover analysis, *kN·m*	*287.56*	*284.76*	*284.78*
13	Maximum shaer force near the anchorage obtained by multimodal pushover analysis, *kN*	*49.0*	*48.73*	*47.77*

4 Results

To estimate the responses error obtained by the multimodal nonlinear static method, it is necessary to compare the results with the responses obtained by the time history the direct dynamic method using the acceleration records Erthq1-3 [17].

Table3. Multimodal nonlinear static method error estimation under the seismic impact Iran, 1978 г. (Erthq1)

Parameter		Time history dynamic method	Multimodal nonlinear static method	Error, %
Horizontal displacement, *mm*	Upper node	*-295.70*	*-282.0*	*-4.63*
	Middle node	*-163.80*	*-159.66*	*-2.52*
	Lower node	*-55.10*	*-54.69*	*-0.74*
Maximum bending moment near the anchorage, *kN·m*		*267.38*	*287.56*	*+7.02*
Maximum shaer force near the anchorage, *kN*		*41.19*	*49.0*	*+15.9*

Table 4. Multimodal nonlinear static method error estimation under the seismic impact El Centro, USA (California) (Erthq2)

Parameter		Time history dynamic method	Multimodal nonlinear static method	Error, %
Horizontal displacement, *mm*	Upper node	*-282.15*	*-270.85*	*-4.00*
	Middle node	*-151.65*	*-153.08*	*+0.64*
	Lower node	*-46.79*	*-51.75*	*+9.58*
Maximum bending moment near the anchorage, *kN·m*		*270.3*	*284.76*	*+5.08*
Maximum shaer force near the anchorage, *kN*		*43.73*	*48.73*	*+10.3*

Table 5. Multimodal nonlinear static method error estimation under the seismic impactKobe, Japan, 1995 г. (Erthq3)

Parameter		Time history dynamic method	Multimodal nonlinear static method	Error, %
Horizontal displacement, *mm*	Upper node	*-268.25*	*-274.0*	*+2.10*
	Middle node	*-140.87*	*-154.2*	*+8.64*
	Lower node	*-46.55*	*-51.95*	*+10.39*
Maximum bending moment near the anchorage, *kN·m*		*271.54*	*284.78*	*+4.65*
Maximum shaer force near the anchorage, *kN*		*43.68*	*47.77*	*+8.56*

To assess the quality of the obtained data, the statistical processing was performed:

- The horizontal displacements average error is 2.16%; standard deviation - 5.59%;
- The bending moment average error is 5.58%; standard deviation -1.03%;
- The shaer force average error is 11.58%; standard deviation -3.13%.

Conclusions

Multimodal nonlinear static method was proposed to take into account the higher vibration modes influence under seismic evaluation.

According to the calculation results, it can be concluded that the proposed methodology calculation is useful.The results difference obtained by the time history dinamic methodcompared to results based on the multimodal nonlinear static method does not exceed 16%.

The developed method allows to evaluate the high-rise structures seismic resistance, as well as buildings and structures irregular in height. Comparing two methods for seismic analysis its clear seems the time-history analisys is relatively more time consuming and costly than multimodal nonlinear static method.

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